Wheat in Bins and Discharge Spouts, and Grain Residues on Floors of Empty Bins in Concrete Grain Elevators as Habitats for Stored-Grain Beetles and Their Natural Enemies

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ABSTRACT Wheat stored in upright concrete bins at seven grain elevators in central Kansas was sampled intermittently for insects over a 2.5-yr period by collecting samples from the upper half of the grain mass, from the discharge spout at the base of the bins, and from residue remaining in empty bins before the 2000 wheat harvest. Samples were taken from the grain mass with a power vacuum sampler (PV) and from the discharge spouts (DS) by dropping grain onto the reclaim belt beneath the bins. The density and species distribution in the residue samples were compared with those found in the DS samples and samples from the grain mass (PV). *Cryptolestes* spp. dominated the insect populations in all types of samples, constituting >40% of all insects in the PV samples in three of five time periods and >60% of all insects in DS samples in four of the five time periods. *Cryptolestes* spp. was an early colonizer, being found in the grain mass shortly after new grain was added. *Rhyzopertha dominica* appeared to be slower to colonize grain and grain residue, but sometimes developed large populations (i.e., 2.4 ± 0.7 adults/kg between July and December 2000). *Sitophilus* spp. weevils often were present in grain masses, were often abundant in grain in the discharge spouts (i.e., 11.1 ± 2.9 adults/kg between July and December 2000), and were abundant in grain residue in empty bins in May/June 2000 (5.3 ± 0.7 adults/kg). Differences in density and species distribution of insects in grain in the upper part of the grain mass and those in the discharge spouts indicated that the populations were not closely related. Grain in discharge spouts usually was densely infested, and parasitic wasps, natural enemies of several of the beetles, were found when the density of the pest insects was greater than ≈10/kg. The population of natural enemies appeared to increase when the density of pest insects increased after a lag of about one month, and decreased when the population of pest insects decreased. Grain in discharge spouts appeared to provide an incubation chamber for pest insects, and removing this grain periodically should reduce the resident populations. Residue in empty bins often was densely infested compared with samples from the grain masses. Cleaning the empty bins before refilling with newly-harvested wheat resulted in a significantly-reduced density of pest insects in discharge spouts later, and the effect lasted at least 12 wk after filling.

KEY WORDS grain elevator, population dynamics, natural enemies

INSECT INFESTATIONS OF stored grain have been traced to various sources (Hagstrum et al. 1995). Outside the United States, the rice weevil, *Sitophilus oryzae* (L.) (Agrawal et al. 1977, Kiritani et al. 1957, Rossitier 1970) and the lesser grain borer, *Rhyzopertha dominica* (F.) (Doharey et al. 1979) are known to infest grain in the field. In the southeastern United States, field infestations of corn by the maize weevil, *S. zeamais* (L.) are common (Williams and Floyd 1970). However, in studies on United States farms (Cotton and Winburn 1941) and in United States elevators (Chao et al. 1953), field infestation of wheat by these species was not observed. Although *R. dominica* was capable of infesting wheat in the field when insects were placed in cages around wheat heads (Hamza 1990), rice weevils did not infest wheat when released in larger field cages covering stands of wheat (Walkden 1951). Thus, it appears probable that field infestation is not a major source of stored-grain insects in wheat storage elevators in the mid-western United States. Rather, resident populations of stored-grain insects are likely to be present in stored grain, spills, static grain or residues in handling equipment, and residues remaining in empty bins. Most grain elevators have grain and grain residues available to insects throughout the year.

Some information is available relative to residual insect infestations and their control in farm-stored grain. In Canada, Smith and Barker (1987) found rusty grain beetles, *Cryptolestes ferrugineus* (Stephens), in the grain residues from 11.9% of 1,752 bins on 296 farms. They found red flour beetles, *Tribolium casta-*

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neum (Herbst), in the grain residue from 2.3% of these bins. In samples of 1.0 −1.5 liters each, a mean of 0.1 *C. ferrugineus* adults and 0.02 *T. castaneum* adults were reported (Barker and Smith 1987). Average densities of larvae were similar, 0.15 and 0.018 per sample for *C. ferrugineus* and *T. castaneum,* respectively. The number of uninfested samples was not related to previous infestation, presence of livestock on the farm, presence of spilled grain, pest management practices used, type of grain stored, or type of storage structure (Barker and Smith 1990).

Sinclair (1982) reported that 85% of insects in the grain residues from 57 northern Australian farm bins consisted of *S. oryzae, R. dominica, Cryptolestes* spp., and *T. castaneum.* In this warm climate, the insect densities per kg of grain residue increased from 44.9 in January (midsummer) to 299.5 in May at the end of the warmest season. The density appeared to decrease during the slightly cooler months, and was 66.4 by the following December. High densities (up to 70 insects/kg) were found in grain residues from combines (Sinclair and White 1980).

On United States farms, Walker (1960) used the release-recapture method to estimate populations of adult *T. castaneum* in 30 empty farm bins (30–300 t each). Insects were recovered in 17 bins and the estimated population ranged from 0 to >160,000 with a mean of 18, 151 *T. castaneum* adults per bin. Ingemansen et al. (1986) found that the percentage of bins infested and the average insect densities in stored oats were correlated with the peak insect density in the grain stored in the bin during the previous year. This suggests that insect infestations were carried over in the bin from one year to the next. Hagstrum (1989) observed that the *C. ferrugineus* present at harvest time moved from the bottom of the bin into newly-harvested wheat stored in the bin. Reed and Pedersen (1987) reported that although treated, empty bins were as likely as untreated, empty bins to contain live insects immediately before harvest, the number of insects observed was consistently smaller in treated bins. Reed and Harner (1998) reported that cleaning and fumigating bins reduced insect densities.

Little of the type of information reviewed above for farms is available for elevator-stored grain. At grain elevators, grain is routinely sampled with a grain trier as trucks or railcars arrive, or with a pelican sampler as trucks are unloaded (Parker et al. 1982). Grain moved on a conveyor belt may be sampled with an Ellis cup, and at many elevators, grain is routinely sampled with an automatic diverter sampler for grading. The grain near the bottom of a bin may be sampled by releasing a small amount of grain onto the reclaim belt, but no information is available on the relationship between the number of insects in these samples and the number of insects in the grain stored in the bin. Surveys indicate that cleaning empty bins to remove the insects and grain residues is a standard practice at most elevators in the United States and Canada (Kenkel et al. 1993, Martin et al. 1997).

As a habitat for grain insects, grain elevators differ from farm storage in the type and size of structures and in the grain handling and insect-control practices. The study described here was done in upright concrete elevators. A grain elevator is a complex of integrated vertical and lateral grain transport devices and storage bins that may contain hundreds of tall, contiguous bins (Fig. 1). Grain enters the storage bins through the spout or port in the bin roof and is released from the bin through the discharge spout at the base. In most cases, both the entry point and the discharge points are located near the inside wall of the bin. Grain flow from the bin is controlled by a slide gate located near the bottom of the discharge spout. In the elevators studied, the slide gates were accessed in the tunnel, where grain flowed from the spouts onto the reclaim belt that carried it to the elevator leg for elevation.

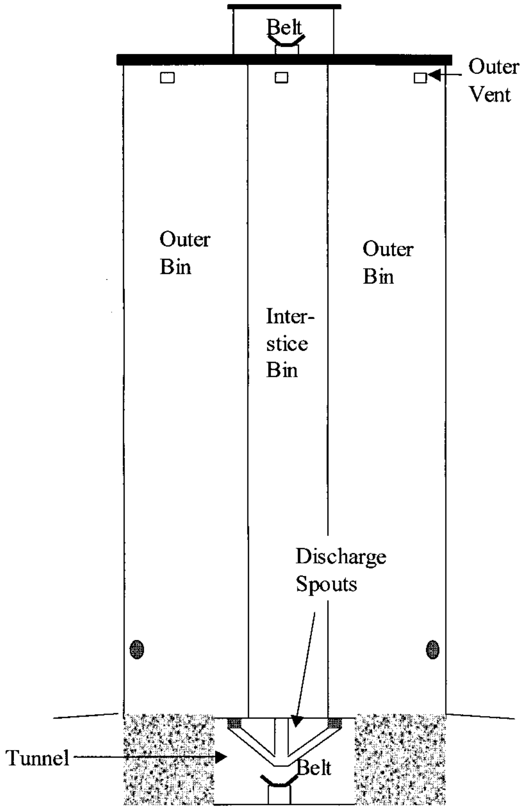

Fig. 1. Illustration of upright storage bins at a grain elevator.

Typically, the bins are filled and emptied several times during the year as different crops are harvested or grain is received from farms or other elevators. Unlike many farms, most elevators have grain of some kind in storage year-round for many consecutive years. That is not to say that the same grain remains in storage for years, but rather, that there never is a period of time when a commodity that could sustain a pest insect population is completely absent from the elevator. Often, grain of the same type and crop year is blended from several bins into an empty bin. This may be done to dilute high moisture grain, warm grain, or grain with some other undesirable condition, or to achieve a mixture containing desired grain quality attributes. The practice of withdrawing grain from one bin and placing it into another often is called "turning." Fumigation usually is done as grain is turned, and often is accomplished by adding fumigant pellets or tablets to the grain just before the grain enters the bin. Fumigation normally is done on a calendar-based schedule, or when insects, heating grain, or damaged grain is noticed.

The present research investigated insect populations in wheat residues in empty bins at grain elevators compared with the insect populations in the upper layers of wheat stored in the bins and wheat in the discharge spouts. The effect of cleaning the bins before refilling on the insect density found later in grain in the discharge spout was also investigated.

Materials and Methods

Grain Elevators. The seven elevators sampled in this study were located in central Kansas. The smallest consisted of 25 bins with a total storage capacity of 5,525 t and the largest had 138 bins with a total storage capacity of 54,690 t. The larger bins at each elevator were typically 27–28 m tall and 6–9 m in diameter. Although some of the elevators had detached bins of metal or concrete, only data from the upright concrete bins that formed part of the main storage structure and contiguous annexes are summarized here. Bins that contained wheat were sampled on several occasions between August 1998 and December 2000. Because most of the bins were filled, emptied, and refilled several times during this period, it was not possible to maintain a uniform sampling interval, and much of the data were from grain not sampled on previous occasions. The number of bins sampled at each site varied according to the amount of wheat in storage at the time of the visit.

Sampling. Stationary grain in the upright, concrete bins was sampled by means of a power vacuum (PV) sampler that collected samples by sucking grain into the end of a rigid tube forced into the grain mass. The grain was accessed at the fill port that, in most cases, was located near the bin wall. Our sampling system consisted of a 5.25-kW, gasoline-powered engine driving a vacuum pump connected to a flexible hose. The power and vacuum units were mounted in a trailer that was towed to the elevator. The hose was hoisted to the bin-top level and connected to a cyclone from which the grain samples were collected. The cyclone was connected to the probe by a short flexible hose. The probe consisted of sections of aluminum pipe 3 cm in diameter and 1.2 m long. New sections were added as the tube was inserted into the grain. The suction at the end of the tube removed the grain immediately adjacent to it as the tube was forced into the grain.

Grain in discharge spouts (DS) was sampled by opening the slide gate and allowing grain to fall from the spout onto a stationary grain transport belt. Approximately 10 kg were allowed to accumulate, from which grain was scooped into a 3.9-L container. Residue samples from empty bins were collected as randomly as possible from the residue remaining in the bin. When the quantity of residue was small, as much of the residue as possible was collected and placed in a sample bag. When a large amount of residue was present, small quantities were collected from different locations and placed in the sample bag.

The quantity of grain in DS and PV samples were standardized by collecting a standard volume of 3.9 liters. Samples were added to a 3.9-L container until it filled and grain flowed over the container on all sides. The surface was then leveled. This produced a sample of ≈3 kg. The samples from the empty bins were transported to the laboratory where the sample weight was recorded and the insect density per kg was calculated.

When samples were taken with the power vacuum sampler, the grain collected as each tube section (1.2-m) was inserted into the grain was added to the 3.9-L container, and the excess was returned to the bin. This provided a 3.9-L sample for each 1.2 m of grain depth as the probe was inserted into the grain mass. In typical bins (6–8 m wide and 26–40 m tall) the sampling rate for PV samples was 0.13–0.07 kg per t of grain sampled. However, in most cases, only 10–14 sections could be added before grain resistance became too great. Thus, only 10–14 samples were collected per bin, and only the top half of the grain mass was sampled. In the third year of sampling, improvements in the probe allowed sampling of the bottom half of the grain. All samples were taken through the grain entry port near the bin wall, where the grain surface was closest to the roof. This allowed sampling to be done inside, sheltered from wind, sun, and rain.

To reduce the size of the samples transported from the sampling sites to the laboratory, PV and DS samples for insect analysis were sieved on-site and the grain was returned to the bin. Regardless of sample type, sieving was accomplished by twice passing the 3.9-L sample over an inclined sieve. Sievings were collected, labeled, and returned to the laboratory for insect analysis. Every seventh grain sample from each bin was returned unsieved to the laboratory for grain quality analysis. Residue samples from empty bins were sieved in the laboratory.

The inclined sieve used to remove insects from the samples consisted of a tubular metal frame with a stainless-steel screen with 1.6-mm, square openings stretched tightly across the top. Material passing through the screen was collected on a pan and directed to a funnel to which a quick-seal plastic bag was attached. A hopper above the screen held the grain sample and a funnel at base of the screen directed material passing over the screen to a container. The inclination of the sieve was 25° from horizontal and the opening of the hopper was adjusted such that the sample passed over the screen in ≈25 s. In laboratory tests, ≈60%, depending on species, of a known quantity of adult insects were removed with these settings. An improved sieve that removed 90–97% of the insects, depending on species, was used after December 1999. This sieve had a screen with 4.0 - mm openings.

Table 1. Numbers of power vacuum and discharge spout samples and bins represented during the five sampling periods reported

Sampling period	Power vacuum			Discharge spout		
	Number samples	No. bin events	Mean no./bin/events	No. samples	No. bin events	Mean no./events
July–Dec. 1998	786	61	12.9	277	183	1.5
Jan.-June 1999	2,400	175	13.7	106	106	1.0
July–Dec. 1999	3,172	265	12.0	334	327	1.0
Jan.-June 2000	3,149	234	13.5	288	288	1.0
July–Dec. 2000	5,487	334	16.4	422	420	1.0
All	14,994	1,069		1,427	1,324	

Sample Analysis. Sievings were analyzed by spreading a small quantity on a flat surface and identifying the live adult beetles. Parasitic wasps, dead or alive, were identified and recorded. Because the wasps are tiny and fragile, it is doubtful they would be present in an identifiable form unless they had been alive when collected.

Statistical Analysis. The data were analyzed using SAS software (SAS Institute 1997). Correlation analysis (PROC CORR) was used to analyze the relationship between insect density in the grain before and after fumigation. Spearman correlation coefficients were calculated because the data were not normally distributed. Frequency distributions of insect density ranges at different times of the year were compared using chi-square analysis (PROC FREQ). Means separation was done by regression techniques (PROC GLM) because of the unequal sample sizes. Least squares means were separated by paired *t*-tests. Means are reported as mean ± SE.

Results and Discussion

Discharge Spouts Compared with the Grain Mass. To compare characteristics of the insect populations in the grain mass with those in the discharge spouts of the same bins, PV samples were compared with samples taken from the DS samples. Overall, nearly 15,000 PV samples and >1,400 DS samples were examined. To facilitate the analysis, data were grouped by six-month intervals beginning in July 1998 and ending with December 2000.

The fewest number of samples taken during any of the five intervals was 786 PV and 277 DS samples collected during the first months of the research from July to December 1998 (Table 1). These samples represented 61 events in which a set of PV samples was taken from an individual bin. An average of 12.9 samples/bin were taken during each such event, one sample for each 1.2-m probe section, each time a bin was sampled during this period. The average number of samples/bin per sampling event increased in 2000 as improved probes allowed for deeper sampling in each bin. The means from each sampling event per bin were used to compute insect density means at each six-month time period. During the first time period there were 183 events in which one or more samples were taken from the discharge spout of a bin. A mean of 1.5 DS samples were taken from each bin during the first 6-mo period. Thereafter, only one DS sample/bin was taken at each sampling event.

No consistent pattern was apparent (Table 2) relating the density of any of the five common species of pest insects in the PV samples with the same species in the DS samples during the same time period. Neither was there a consistent pattern within sample types by season. Correlation coefficients of the density of all insect species combined in the PV compared with DS were 0.16, 0.22, 0.3, and 0.94 in the last four time periods. Although three of the four correlation coefficients were significantly different than zero, this significance was probably an artifact. In all such cases, the majority of the data pairs consisted of zero density in both types of samples, and one or two pairs of

Table 2. Mean density of five pest insects commonly collected from PV and DS samples

Sampling period	*Cryptolestes* spp.	*R. dominica*	*Oryzaephilus* spp.	*Sitophilus* spp.	*Tribolium* spp.	Total
	Power vacuum (mean number/kg ± standard error)					
July–Dec. 1998	0.001 ± 7.23	<0.001 ± 2.11	0.001 ± 0.57	<0.001 ± 0.92	<0.001 ± 0.61	0.003 ± 8.18
Jan.-June 1999	0.062 ± 0.52	0.004 ± 0.01	0.019 ± 0.06	<0.001 ± 0.04	0.044 ± 0.03	0.129 ± 0.54
July–Dec. 1999	0.672 ± 3.44	0.535 ± 1.17	0.020 ± 1.23	0.178 ± 0.64	0.083 ± 0.13	1.489 ± 4.42
Jan.-June 2000	0.197 ± 3.34	0.377 ± 0.28	0.005 ± 0.56	0.077 ± 0.64	0.024 ± 0.03	0.681 ± 3.81
July–Dec. 2000	1.107 ± 2.84	2.402 ± 0.66	0.008 ± 0.44	0.020 ± 3.27	0.532 ± 11.71	4.07 ± 12.66
	Discharge spout (mean number/kg ± standard error)					
July–Dec. 1998	16.30 ± 4.17	2.58 ± 1.22	1.04 ± 0.33	2.67 ± 0.53*	1.14 ± 0.35	23.73 ± 4.73*
Jan.-June 1999	1.88 ± 0.67*	0.3 ± 0.13	0.18 ± 0.08	0.13 ± 0.05*	0.04 ± 0.04	2.54 ± 0.70**
July–Dec. 1999	18.71 ± 3.10**	3.23 ± 1.06	4.15 ± 1.11*	2.38 ± 0.58*	0.50 ± 0.12*	28.96 ± 3.98**
Jan.-June 2000	22.05 ± 3.01**	1.13 ± 0.25*	2.20 ± 0.50**	1.03 ± 0.58	0.11 ± 0.03*	26.52 ± 3.43**
July–Dec. 2000	13.71 ± 2.53**	2.86 ± 0.59	0.70 ± 0.39	11.05 ± 2.92*	19.21 ± 10.44	47.52 ± 11.29*

Mean density in the discharge spout samples significantly different (* $P < 0.05$ or ** $P < 0.01$) from that in the power vacuum samples.

Table 3. Percent of all insects belonging to each of five species of beetles collected from power vacuum (PV) and discharge spout (DS) samples

Sampling period	Species									
	Cryptolestes spp.		*Rhyzopertha dominica*		*Oryzaephilus* spp.		*Sitophilus* spp.		*Tribolium* spp.	
	PV	DS	PV	DS	PV	DS	PV	DS	PV	DS
July–Dec. 1998	44.4	68.7	11.1	10.9	33.3	4.4	11.1	11.3	0	4.8
Jan.-June 1999	48.2	74.3	3.2	11.9	14.7	7.1	0	5.1	33.9	1.7
July–Dec. 1999	45.2	64.6	35.9	11.1	1.4	14.3	12.0	8.2	5.6	1.7
Jan.-June 2000	29.0	83.1	55.4	4.3	0.8	8.3	11.4	3.9	3.5	0.5
July–Dec. 2000	27.2	28.8	59.0	6.0	0.2	1.5	0.5	23.3	13.1	40.4

samples contained high insect densities in both types of samples. This resulted in the appearance of a significant correlation although no relationship was observed in the graphed data.

The DS samples consistently contained insect densities ranging from tens to thousands of times greater than those in the PV samples. In all five time periods, the mean density of all species combined was significantly different by paired *t*-tests in the two types of samples, and means for individual species were significantly different in 13 of 25 cases.

Insect populations in the grain mass (PV) and in the discharge spout (DS) often differed in terms of species distribution (Table 3). *Cryptolestes* spp. dominated the populations in the discharge spouts except for the final time period, in which large numbers of *Tribolium* spp. were present. *Cryptolestes* spp. is consistently among the first species to arrive in newly-harvested wheat, often colonizing rapidly in large numbers (Hagstrum 2001). In contrast, *Rhyzopertha dominica* never represented >12% of the insects in the DS samples, despite comprising more than half the insects in the grain mass during two time periods. This species is less mobile and requires a longer period of time to establish a colony (Hagstrum 2001). The *Sitophilus* spp. weevils sometimes constituted a significant proportion of the populations in each of the two types of samples, but not during the same time periods. The presence of a substantial proportion of *Tribolium* spp. was also variable, but the proportions did not change in parallel in the two types of samples.

The lack of true correlation in terms of insect densities and the dissimilarities in population characteristics appears to indicate that a sample from the discharge spout does not provide insight into the insect density or species infesting the top of the grain mass. From the data collected during the first half of 2000, 81 bins were identified where none of the PV samples contained insects. The discharge spout samples taken from these bins contained 23.6 ± 4.8 beetles per kg, 18.4/kg ± 3.6 of which were *Cryptolestes* species, although all five common species were present. Only 16% of the bins with insect-free PV samples had no insects in the DS sample, and an approximately equal number contained >50/kg. These results provide evidence that insects living in the discharge spouts represent a different population than those located in the upper part of the grain mass.

Pest Insects and Natural Enemies in the Discharge Spout. Because the grain in the discharge spout consistently contained a high density of pest insects, the DS samples appeared to provide an opportunity to examine the relationship between natural populations of stored-grain insects and natural populations of their natural enemies. Sampling for natural enemies was problematic because those found were tiny wasps. Because live wasps readily escape from grain samples during sampling and sieving, and because dead wasps are fragile and easily broken into unidentifiable fragments, the detection rate was undoubtedly low. Nevertheless, in most cases, natural enemies were detected when the pest insect density exceeded ≈10/kg, and the population densities of the natural enemies generally mirrored the population growth trends of the pest insects (Fig. 2). For example, in late 1999, the population of pest insects increased greatly, then decreased after the grain was fumigated. The number of natural enemies per kg also increased greatly before the fumigation, and the pattern of growth and decline mirrored that of the pest insects.

Residue from Empty Bins. In early summer, most grain elevators in the study area were being prepared to receive the annual wheat harvest in June/July, and many bins had been emptied. In May and June 2000, the grain residue remaining in bins after the grain was discharged was sampled and the quantity of residue on bin floors was estimated. Some of this grain residue was from corn or grain sorghum that had been stored in the bins. One hundred forty-seven samples were taken from 74 bins in which it was likely that newly-harvested wheat would be stored. Other bins were not sampled but were examined before refilling to determine if they had been cleaned. The mean quantity of grain residue in the hopper-bottom bins was estimated to be 192 ± 0.5 kg. Based on the density of insects in the samples and the estimated quantity of grain, a mean of >3,000 insects per bin would have been present to infest new grain. Pest insects were recovered from 77% of the grain residue samples. *Cryptolestes* spp. was the most common and most numerous pest (Table 4), constituting 45% of all insects, and being found in about two-thirds of the bins. *Sitophilus* weevils constituted nearly one-third of the population and were found in about one-third of the bins. The other three common beetles constituted less than one quarter of the population and were less frequently detected.

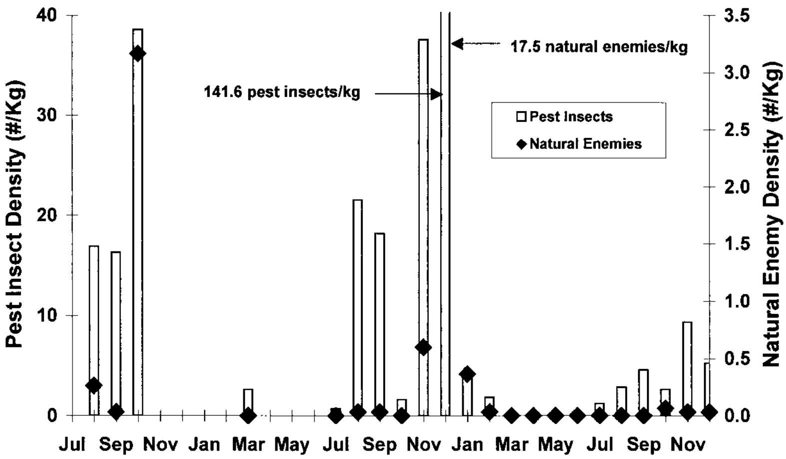

Fig. 2. Mean density of pest insects, all species combined (bars) and natural enemies, all species combined (diamond) in wheat from discharge spouts of upright concrete bins at grain elevators in Kansas.

Twelve specimens of natural enemy species were collected from the empty bin samples, and at least one wasp was recovered from 21% of the samples infested by pest insects. No natural enemy was found in any sample that was free of pest insects. This was an expected and significant ($\chi^2 = 4.27, P < 0.05$) result. The mean density of natural enemies (0.31/kg) in the empty bin samples was greater than the mean density of natural enemies in the discharge spout samples at most sampling times. This may reflect the relatively greater access to host insects in the residues in empty bins compared with those in the discharge spouts. The density of natural enemies was less in the empty bin samples than in the discharge spout samples only during a three-month period in the winter of 1999/2000 when the density of both pest insects and natural enemies was exceptionally great in the discharge spouts (Fig. 2).

The type of grain residue (wheat versus corn/sorghum) did not significantly affect the species distribution of pest insects or the overall insect density. Nevertheless, it may be noteworthy that the internal-infesting insects *R. dominica* and *Sitophilus* spp. constituted nearly half of the population in wheat but less than one-third of the population in corn and grain sorghum residues (Table 5). One densely infested sample was excluded as an outlier to avoid skewing the data and complicating the interpretation for the other bins. The mean density of all pest insects varied greatly, but not significantly, by elevator. At two elevators, the mean density of pest insects in empty bin samples was ≈68.5/kg. At two other locations the mean density was ≈35/kg, and at one location the density was only 15.3/kg. Chi-square analysis of the frequency distribution of all species combined demonstrated no significant effect of elevator on any species or on all pest insects or natural enemies combined. This indicates that pest insects were ubiquitous in May and June when the empty bins were sampled.

Table 4. Density of insects commonly collected from residues in empty bins

Species	Mean number/kg ± standard error	Percent of population	% Bins with spp. present
	Pest insects		
Cryptolestes spp.	7.40 ± 2.50	45.0	64.9
Rhyzopertha dominica	1.48 ± 0.68	9.0	20.3
Oryzaephilus spp.	0.50 ± 0.42	3.0	20.3
Sitophilus spp.	5.33 ± 2.42	32.4	37.8
Tribolium spp.	1.73 ± 0.77	10.6	28.4
All pest species	16.44 ± 4.97		77.0
	Natural enemies		
Habrobracon hebetor	0.023 ± 0.015	7.4	4.1
Anisopteromalis	0.039 ± 0.033	12.5	6.8
Theocolax elegans	0.003 ± 0.002	1.0	2.7
Cephalonomia waterstonii	0.247 ± 0.235	79.1	6.8
All natural enemies	0.312 ± 0.237		16.3

All bins (n = 74) from which samples were taken are included.

Discharge Spouts Sampled Shortly After Bins were Filled with New Wheat. Samples were taken from discharge spouts 46 ± 1.1 d after bins were filled with newly-harvested wheat. The mean insect density was significantly lower in bins that had been cleaned before filling (Table 6) in the case of *Cryptolestes* spp. ($F = 7.3$, df = 84, $P < 0.01$), *Oryzaephilus* spp. ($F = 4.3$, df = 84, $P < 0.05$) and all pest insects combined ($F = 4.9$, df = 84, $P < 0.05$). Categorical analysis in which samples were classified by insect density (either 0, 0.1–9.9, or ≥10/kg) indicated that bin cleaning was significantly ($\chi^2 = 15.2$, df = 2, $P < 0.01$) associated with the frequency distribution of density ranges in most individual species and for all pest insects combined (no table shown). When all pest insect species were considered together, 48.8% of samples from cleaned bins were free of insects, and only 12.2% of the samples were densely infested. In samples from bins that had not been cleaned, only 11.4% were free of insects and 31.8% were densely infested. The effect of bin cleaning was confounded by elevator effect be-

Table 5. Density of insects commonly collected from residues in empty bins by type of grain residue

Species	Wheat		Corn, grain sorghum, or mixed	
	Mean number/kg ± standard error	% of population	Mean number/kg ± standard error	% of population
Cryptolestes spp.	8.65 ± 3.80	40.7	11.86 ± 7.65	55.3
Rhyzopertha dominica	2.97 ± 1.43	14.0	0.45 ± 0.43	2.1
Oryzaephilus spp.	1.07 ± 0.91	5.0	0.02 ± 0.01	0.1
Sitophilus spp.	6.82 ± 4.60	32.1	5.40 ± 3.44	25.2
Tribolium spp.	1.75 ± 1.19	8.2	3.73 ± 2.32	17.4
All pest species	21.26 ± 26.11		21.46 ± 31.74	
Habrobracon hebetor	0.05 ± 0.03	71.4	0 ± 0	0
Anisopteromalis calandrae	trace	4.8	0.16 ± 0.14	82.8
Theocolax elegans	0.01 ± 0	9.5	0 ± 0	0
Cephalonomia waterstonii	0.01 ± 0.01	14.3	0.03 ± 0.02	17.2
All natural enemies	0.07 ± 1.65		0.19 ± 2.01	

Only bins in which the grain type was known are included (34 wheat, 22 corn or grain sorghum), and one outlier was excluded.

cause in some elevators all bins were cleaned whereas in other elevators no bins were cleaned. Analysis of the frequency distribution of uninfested, moderately infested, and densely infested samples, as described above, showed that the distribution was significantly different depending on the elevator for most species and for all pest insects combined. That this was not true in the case of residue samples from empty bins appears to indicate that the observed effects are a result of bin cleaning, not elevator.

Insect density in the DS samples taken 46 ± 1.1 d after bin filling was not significantly correlated ($r < 0.35$, $n = 51$, $P > 0.05$) with that in residue samples taken from the empty bins that were cleaned immediately before filling. This was true for each species individually and for all species combined. This also supports the interpretation that significantly different means in the DS samples were due to bin cleaning. If cleaning had not been done, a positive relationship would be expected, as insects from grain residue densely infested with a given insect would have contaminated the DS sample taken from the spout 46 d later.

After an additional 40 ± 3.4 d, samples were again taken from the discharge spouts of 63 bins, 45 of which had been cleaned before harvest and 18 had not. The density of *Cryptolestes* spp. ($F = 15.7$, df = 62, $P < 0.01$), *Sitophilus* spp. ($F = 14.1$, df = 62, $P < 0.01$), *Tribolium* spp. ($F = 28.2$, df = 62, $P < 0.01$), and all pest insects combined ($F = 24.8$, df = 62, $P < 0.01$) was significantly lower when bins had been cleaned (Table 7). This indicated that the effects of bin cleaning lasted at least three months.

However, the data provided further evidence that immigration was a major factor in colonization of grain in the discharge spouts. *Tribolium* spp. constituted ≈35% of the population in DS samples taken within a few months after the 2000 harvest (Tables 6 and 7). This was a much higher proportion than was observed in previous years (Table 3) and very different than that observed in the empty bins (Table 5).

Conclusions

The large number of samples taken from the grain masses and the discharge spouts allowed researchers to evaluate several aspects of pest insect ecology in grain elevators. This provided insights into how grain stored in elevators should be sampled for insects and the effectiveness of bin cleaning on insect populations. Better sampling methods and an understanding of the population dynamics of insect infestations in grain residues in empty bins, in the discharge spout, and in the grain mass should be helpful in developing more effective pest management programs.

Grain in the discharge spout contained detectable populations of pest insects most of the time, and the densities were frequently high. Natural enemies were detected in the discharge spout samples whenever the pest insect density became high. The pattern of nat-

Table 6. Mean density of insects commonly detected in discharge spout samples 49 days after the bins were filled

Species	Bins cleaned prior to filling		Bins not cleaned prior to filling	
	Mean number/kg ± standard error	% of population	Mean number/kg ± standard error	% of population
Cryptolestes spp.	0.7 ± 0.31*	14.4	2.3 ± 0.49	8.7
Rhyzopertha dominica	1.1 ± 1.10	22.6	1.33 ± 1.24	5.0
Oryzaephilus spp.	0 ± 0**	0	0.07 ± 0	0.3
Sitophilus spp.	2.9 ± 1.44	60.3	13.4 ± 5.61	50.4
Tribolium spp.	0.1 ± 0.05	2.1	9.5 ± 7.21	35.6
All pest species	4.9 ± 2.01**		26.6 ± 9.25	
All natural enemies	0.02 ± 0.01		0.4 ± 0.32	

There were 41 bins cleaned and 44 bins not cleaned prior to filling.
Mean from cleaned bins significantly different (* $P < 0.01$ or ** $P < 0.05$) than mean from uncleaned bins.

Table 7. Mean density of insects commonly detected in discharge spout samples 89 days after the bins were filled

Species	Bins cleaned prior to filling		Bins not cleaned prior to filling	
	Mean number/kg ± standard error	% of population	Mean number/kg ± standard error	% of population
Cryptolestes spp.	1.48 ± 0.84*	32.7	10.06 ± 2.79	14.6
Rhyzopertha dominica	0.87 ± 0.81	19.1	0.76 ± 0.49	1.1
Oryzaephilus spp.	0.50 ± 0.30	11.1	1.11 ± 0.87	1.5
Sitophilus spp.	1.48 ± 0.69*	32.7	32.96 ± 13.29	47.8
Tribolium spp.	0.20 ± 0.11*	4.4	24.15 ± 7.21	35.0
All pest species	4.53 ± 1.49*		69.03 ± 20.41	
All natural enemies	0 ± 0		0.11 ± 0.09	

There were 45 bins cleaned and 18 bins not cleaned prior to filling.
Mean from cleaned bins significantly different (* $P < 0.01$) than mean from uncleaned bins.

ural enemy population build-up and decline following the build-up and decline of the host insects appeared to be similar to those described for other ecosystems. The lack of sensitive sampling techniques for natural enemies probably limited the ability to accurately describe this phenomenon.

The insect populations in the discharge spouts were different than those in the upper part of the grain mass in terms of density and species distribution. Grain in discharge spouts appears to be an accessible habitat suitable for rapidly developing and sustaining insect populations. The insects may enter the bin through small openings around the discharge slide gate or originate from insects remaining in the grain residue after the bin has been emptied. Therefore, discharge spouts should be considered a focal point of an elevator sanitation program. That is, grain in the spouts, much like spillage, empty bin residues, or other grain residues in the elevator, functions as an accessible habitat that can easily be removed and fumigated as part of a program to suppress the total insect population.

Cryptolestes spp. often dominated populations, both in the grain mass and in the discharge spouts. For 18 mo, it constituted >40% of the pest insects collected from the grain mass and for two years it constituted >60% of the pest insects collected from discharge spouts. In grain residues from empty bins, it constituted 45% of all insects and was present in nearly two-thirds of the residue samples. Because *Cryptolestes* spp. does not damage the grain, the presence of this species in fairly large numbers does not constitute a threat to grain quality. Rather, it must be managed such that its presence does not trigger a price discount when the grain is sold or shipped.

R. dominica was present in all types of samples throughout the study, but appeared to be slower to colonize and establish large populations than were most of the other species. This was apparent because it constituted only 9% of the residues in empty bins and was present in only one-fifth of the samples. In discharge spouts, *R. dominica* constituted <12% of the population in all time periods. However, it dominated the population in the grain mass (PV samples) throughout the year 2000. During this period of time, the wheat stored in the study elevators was at least 6 mo old, and most was >18 mo old. Because *R. dominica* damages the grain and can lead to severe losses, it must be managed. The fact that populations build slowly should allow time for managers to detect and control this insect.

Residue in empty bins appears to be attractive to stored-grain insects in the months before wheat harvest. It contains much broken grain and grain dust, is readily accessible, and the temperature of the residue and the environment during this time is favorable for insect development. Therefore, it was not surprising that ≈80% of the samples of grain residue from empty bins was infested, nor that the overall mean insect density was high. This residue appeared to be especially attractive to *Sitophilus* spp. weevils. The weevils constituted a higher percentage of the population and had a higher mean density in the empty bin residues than in the discharge spout samples or the samples from the grain mass.

Cleaning empty bins resulted in a reduced density of pest insects in the discharge spouts at about six weeks and again nearly 3 mo after the bins were filled. Empty bin cleaning appears to be an effective way to reduce the resident population of all insects, especially *Sitophilus* weevils.

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